A NEPTUNE/TRITON VISION MISSION USING NUCLEAR ELECTRIC TECHNOLOGIES*
3rd INTERNATIONAL PLANETARY PROBE WORKSHOP,
27 June – 1 July 2005, Anavyssos, Attica, Greece

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ABSTRACT

Over one year ago, our response to a NASA Research Announcement (NRA) for Space Science Vision Missions resulted in the award of a NASA Vision Mission contract to study a Neptune Orbiter with Probes mission using nuclear electric power and propulsion (NEP). Our national team of engineers and scientists from industry, academia, NASA centers and the Southwest Research Institute, with the assistance of JPL's Team X, has developed a mission concept that satisfies the science goals and objectives of studying the Neptune system. In this report we describe the science goals and highlight the numerous engineering challenges that must be resolved in order to accomplish this ambitious mission.

The giant planets of the outer solar system divide into two distinct classes: the gas giants Jupiter and Saturn, primarily comprising hydrogen and helium, and the ice giants Uranus and Neptune that are believed to contain much higher proportions of the heavier elements including oxygen, nitrogen, carbon, and sulfur relative to hydrogen. Detailed comparisons of the internal structures and compositions of the gas giants with those of the ice giants will yield valuable insights into the processes that formed the solar system and, by extension, extrasolar systems. To date, Pioneer, Voyager, Galileo and Cassini have yielded significant information on the chemical and physical properties of Jupiter and Saturn. A Neptune mission would deliver the corresponding key data for an ice giant planet.

Recognizing the tremendous spacecraft resources made available by nuclear electric power and propulsion, our science team specified that Neptune's fascinating moon, Triton, be included as another target for *in situ* scientific research. This addition makes sense when the realities of transit time to Neptune and the lure of Triton's mysteries, partially revealed by Voyager, are

* The work discussed in this paper was funded under a NASA Visions Contract, NNH04CC41C.

considered. A NEP Neptune mission may be the only Neptune mission conducted in this century. It therefore makes sense to study the entire Neptune planetary system.

Although our overall plan is a Neptune Orbiter with Probes mission utilizing nuclear electric power and propulsion to study Triton, Nereid, and the other icy satellites of Neptune, Neptune's system of rings, and the deep Neptune atmosphere to a depth of at least 100 bars, the science goals and objectives pertain to any detailed study of the Neptune system. Such a grand mission, using nuclear electric technologies requires that a number of technical issues be investigated and resolved, including: (1) developing a realizable mission design that allows proper targeting and timing of the entry probe(s) while offering adequate opportunities for detailed measurements of Triton, the other icy satellites, and ring science; (2) giant-planet atmospheric Probe thermal protection system (TPS) design; (3) Probe mechanical design including seals, windows, penetrations and inlets, and pressure vessel; (4) Probe telecommunications through the dense and absorbing Neptunian atmosphere; (5) designing Triton Landers to conduct an extended surface science mission; and (6) within NEP mass and power constraints, defining an appropriate suite of Orbiter, Probe, and Lander science instruments to explore the depths of the Neptune atmosphere, its rings and magnetic field, Triton, and the icy satellites. A driving factor in the design of all three vehicles is the need to maintain a fully operational flight system during the lengthy transit time from launch through Neptune encounter, and beyond.

Our poster summarizes the results of our year-long study by describing the science goals of the NEP Neptune Orbiter with probes mission and discussing the abundant engineering challenges that must be resolved before such a significant mission can be conducted.

SECTION 1: SCIENCE AND MEASUREMENT OBJECTIVES

The complexity and scientific richness of the Neptune systems requires a well-defined list of science and measurement goals and objectives, and a highly integrated suite of remote sensing and *in situ* instruments. A detailed discussion of the specific goals and required instrumentation is beyond the scope of this paper. However, a listing of important science goals and issues in the Neptune system can be found in [1]. The Neptune Orbiter with Probes and Lander (NOPL) Science Goals and Objectives are listed in Table 1.

In the following tables of instruments (Tables 2 through 4) the numbers in parentheses following each Measurement Goal refer to a Science Goal in Table 1. Estimated values for mass, power and data rate were developed jointly with JPL's Team P.

Table 1. NOPL Science and Measurement Objectives

1. <u>Origin and evolution of Ice Giants</u> – Neptune atmospheric elemental ratios relative to Hydrogen (C, S, He, Ne, Ar, Kr, Xe) and key isotopic ratios (e.g., D/H, $^{15}N/^{14}N$), gravity and magnetic fields. [Probes, Orbiter]
2. <u>Planetary Processes</u> – Global circulation, dynamics, meteorology, and chemistry. Winds (Doppler and cloud track), trace gas profiles (e.g.., PH_3, CO, orth/para hydrogen); cloud structure, microphysics, and evolution; photochemistry and tracers of thermochemistry (e.g. disequilibrium species). [Probes, Orbiter]
3. <u>Triton</u> – Origin, plumes, atmospheric composition and structure, surface composition, internal structure, and geological processes. [Orbiter, Lander]
4. <u>Rings</u> – Origin / evolution, structure (waves, microphysical, composition, etc.) [Orbiter]
5. <u>Magnetospheric and Plasma Processes</u> [O]
6. <u>Icy Satellites</u> – Origin, evolution, surface composition and geology. [Orbiter]

Candidate Instrument Payloads

Probe instrumentation, listed in Table 2, is similar to that flown on Galileo and Huygens, including a Gas Chromatograph/Mass Spectrometer (GCMS), sensors for measuring temperature, pressure and acceleration, solar and IR radiometers, and a nephelometer. As illustrated in Table 3, the Orbiter is the core of the Neptune mission, providing a remote sensing platform and in-situ instruments to study Neptune and Triton, as well as providing primary data links to directly return Orbiter science data and as a relay for return of Probes and Lander data. A key element of the Orbiter instrument payload would be an integrated imaging package comprising multiwavelength imagers and spectrometers and a microwave radiometer. Space physics detectors might include a magnetometer and a plasma wave detector. An Ion and Neutral Mass Spectrometer could obtain chemical and isotopic measurements from the atmosphere of Triton. Radio science investigations would be enhanced by including an uplink capability enabled by ultrastable oscillators. Finally, the instrumentation for the Triton Lander is described in Table 4.

Mission Description

The main characteristics of this mission are described in Tables 5 – 9 and in Figure 1. Although NEP provides great flexibility in mission design, it does drive the mission duration. A Jupiter flyby has been included in the assumptions for the mission design since it reduces the transit time from Earth-to-Neptune by several years. The main challenge in performing the probes mission is to release each probe and then perform a deflection maneuver to prevent the Orbiter from following each probe into the Neptune atmosphere. The Lander mission design includes two Orbiter flyovers to receive the burst-transmitted Lander data and relay it to Earth.

Table 5. Mission Summary

- Launch in Jan 2016
- Jupiter flyby in 2020
- Probe Entries in Jan and July 2029
- Probe #1 on prograde entry
- Probe #2 on retrograde entry
- Probe data return for 5 hours after entry
- Triton Orbit in Oct 2033
- Lander released following Triton orbit

Table 6. Mission Phases

Phase	Description
1	Launch, Jupiter gravity assist, to first probe separation (62 days before entry)
2	First deflection maneuver, 70° plane change, Probe 1 entry and observation
3	Probe 2 release, second deflection maneuver, Probe 2 entry and observation
4	Transfer to Triton orbit, Lander separation

Table 7. Orbiter Mission Summary

Parameter	Specification
Trajectory Type	Jupiter Gravity Assist to Neptune Capture
Power (kW)	200
Isp (sec)	7500
Efficiency	75%
Initial C3 (km2/s2)	10
Initial Mass (kg)	36,000
Minimum Jupiter Flyby Radius	5Rj
* Indicated DV is for the Probes and Lander missions only - ΔV for Orbiter tour of Neptune following Probes and Lander missions not included	

Table 8. Probes Mission Summary

Parameter	Probe #1	Probe #2
Altitude at Entry (km)	1000	1000
Entry Flight Path Angle	-40°	-45°
Probe-Orbiter Aspect Angle at Entry	10°	32°
Aspect Angle at Entry + 5 hours	17°	35°
Maximum Aspect Angle	36°	44°
Maximum Range to Orbiter (km)	355,000	500,000
Latitude at Entry	1.3°	70°
Probe Descent	200 bars	200 bars
Data Rate	1.2 kbps	1.2 kbps
Data Volume	21.6 Mbits	21.6 Mbits

Table 9. Lander Mission Summary

Parameter	Specification
Descent to surface	Dual mode biprop (low temperature, storable gels)
Mission Duration	54 days
Data transmission	2 separate burst transmissions with Orbiter visibility
Data Rate	16 kbps
Data Volume	100 Mbits

Technology Development Needs and Issues

Nearly every aspect of the NOPL mission challenges the engineering community to develop spacecraft subsystems in order support the mission. For the Orbiter, accommodation of the fusion reactor presents a unique set of challenges that will be discussed in the next section. Other Orbiter technology challenges include development of electric thrusters for extremely long duration firing and refinement of mission planning tools to accommodate the complex mission that was discussed earlier.

Probe technology development requirements include a thermal protection system necessary to insulate the science instruments and probe subsystems from the extreme heat generated as the probe enters the thick Neptune atmosphere. Other Probe technologies requiring development include pressure vessels capable of sustaining their seals throughout the 13 year cruise from launch to Neptune encounter and that then prevent the Neptune atmosphere from entering the Probes during the descent to the 100 to 200 bar level. The pressure vessel design is further challenged by the need to provide numerous windows and inlets required for the science instruments to ingest and image the atmosphere during descent.

Both the probe thermal design and battery are also quite challenging. While the Probes are attached to the Orbiter, the NEP source will provide adequate power to maintain the electronics and mechanical systems above their survival limits. But once the Probes are separated from the Orbiter, as they cruise toward Neptune and descend into the atmosphere, the combination of the self-contained thermal system and battery energy will be required to maintain all equipment above survival limits. Then, as the probes instruments and high power transmitter are powered, the opposite thermal challenge occurs. The heat dissipated by all the electronics, particularly the high power transmitter, must be managed to prevent all electronics from overheating. A final probe technology challenge is the design of an efficient, high power transmitter.

(Text continues following Tables 2, 3 and 4)

Table 2. Probe Instruments

Instrument	Measurements (Referenced to Science Goals and Objectives)	Mass CBE (kg)	Power Instrument (W)	Power Heaters (W)	Data Rate Compressed (bps)	Data Rate Rate (bps)	Notes on Use / Heritage / Additional Comments
Gas Chromatograph Mass Spectrometer (GCMS)	• Profiles of N_2, HCN, H_2S, NH_3 CH_4 H_20, etc.: Stratosphere to deep atmosphere (1,2) • D/H (1) • 15N/14N (1) • Disequilibrium species (2, 1) • Hydrocarbons (1,2) • Noble gases (He, Ne, Ar, Kr, Xe) (1) • Isotopic ratios (1)	8	10	5	1	2.5	Stand-alone GC and MS experiments have been flown on Venus Probes. An MS was flown on the Galileo Jupiter Probe [2]. A GCMS flew on the Huygens probe as part of the Cassini-Huygens mission. This is the first priority instrument on the probe. Must keep GCMS at 10-20 deg C (the instrument temperature must be maintained in this rage. Could have up to 5kbps of data rate with compression and the new algorithms available
Atmospheric Structure Instrument (ASI) – includes 3-axis accelerometers: x, y, z and redundant z	• Density (2) • Temp/pressure profile (2) • Wind dynamics (2)	4	4	0	0.1	1	Used in many planetary probe missions including those to Venus, Mars, Jupiter and Triton. This is the second priority instrument on the probe. It provides two pressure readings, two temperature readings, and 3-axis accelerometer readings (x,y,z, and redundant z) every second The ASI must be internally redundant because if it is lost, then there will be significant science loss on the GCMS as well.
Net Flux Radiometer (NFR)	• Radiative balance and internal heat (1,2)	1	3	2	0.025	0.0625	Used on Jupiter and Venus probes. Conceptually, this instrument is a basic diode with filters.
Nephelometer	• Cloud particle size/density, microphysical properties (2)	2	4	0	0.01	0.025	Number and size distribution of cloud particles. The nephelometer could possibly be included in the ASI The 2 kg mass includes a 1 kg arm to separate the sensor from the target. the high number density per cubic cm.
HAD	• Detailed helium measurements (1)						Some redundancy with the GCMS. This instrument is included as an optional candidate for inclusion on the probes. It is not included in the pass, power or data rate.
Ortho/Para H_2 Experiment	• Vertical atmospheric transport (2)	1	1	0	0.01	0.024	This is the only instrument in this suite that has not flown. The raw data rate will be 10's of kbps -- it may possibly be higher than the 0.025 indicated here.
Lightning Detector	• Lightning (2)	1	2	0	0.005	0.0125	Galileo probe instrument. This instrument is essentially an AM radio.
Doppler Wind Experiment (DWE)	• Vertical Profile of zonal winds, atmospheric waves (2)	2.1	2.5	2.5	0	0	Flown on Galileo and Huygens probes. Implemented with ultra-stable oscillator done through RF transmission between Probe and Orbiter. The data rates are listed as 0 because it is part of the transmission between the probe and the orbiter.

Table 2. Probe Instruments

Instrument	Measurements (Referenced to Science Goals and Objectives)	Mass	Power		Data Rate		Notes on Use / Heritage / Additional Comments
		CBE (kg)	Instrument (W)	Heaters (W)	Compressed (bps)	Rate (bps)	
ARAD (analog resistance ablation detector)	• TPS recession as a function of time, allows for determination of flight aerodynamics and aerothermal loads (1,2)	0.3	0.9	0	0.004	0.01	Provides science and engineering data. A must for planetary entry probes.
Totals		**19.4**	**27.4**	**9.5**	**1.154**	**3.635**	

Table 3. Orbiter Instruments

Instrument	Measurements (Referenced to Science Goals and Objectives)	Mass	Power		Data Rate		Notes on Use / Heritage / Additional Comments
		CBE (kg)	Instrument (W)	Heaters (W)	Compressed (bps)	Rate (bps)	
High Resolution UV Spectrometer	• Neptune thermospheric and auroral emissions, occultation number density profiles (2) • Triton: atmospheric emissions, occultation number density profiles, surface composition, lander context (3) • Rings: composition (4)	TBD	TBD	TBD	TBD	TBD	Instrument resources not evaluated.
High Resolution IR Spectrometer	• Thermal imaging on nightside (2) • Atmospheric composition (1, 2) • Triton and icy satellite surface composition/roughness and temperature (3, 6) • Lander context (3)	25	20		1300	3250	For the imaging spectrometer, a slit with a push broom approach will be used. The power listed is generous, but since the Orbiter power is assumed to be essentially unconstrained, this is the estimate. A 100m resolution is desired (to be an order of magnitude better than Voyager).
High Resolution (wide angle) Camera	• Triton Surface, geological mapping (3) • Triton Lander context (3) • Rings: waves, structure and dynamics (4) • Neptune Atmosphere, meteorology, dynamics, storm evolution, and lightning (2) • Icy Satellites (6)	2.5	3		180		A 4K by 4K pixels and 600mm focal length camera is assumed. An open issue exists: what is the resolution of this camera at 200km altitude? It was assumed to be 200m. If a factor of 10 better resolution than Voyager is desired, the focal plane will have to be quite large, or double that of Voyager. It should be noted that Cassini used the same optics as Voyager.

Table 3. Orbiter Instruments

Instrument	Measurements (Referenced to Science Goals and Objectives)	Mass	Power		Data Rate		Notes on Use / Heritage / Additional Comments
		CBE (kg)	Instrument (W)	Heaters (W)	Compressed (bps)	Rate (bps)	
IR spectral imager (CIRS)	• Neptune: detailed atmospheric composition, thermal mapping (3-D wind fields) (1,2) • Triton: surface thermal mapping (3) • Rings: particle size and thickness (4)						The Cassini Orbiter CIRS, or Composite Infrared Spectrometer, weighed approximately 39.25 kg and consumed 26.4 watts. The data rate is 6 kbps. No values have been booked in this summary since there is uncertainty in the state of development for this instrument in the 2015 timeframe.
INMS	• Ion / neutral mass spectrometer (3,5)	9.3	27.7		1.5		
Ka/X/S-band radio science	• Atmospheric pressure, temperature profile, density (2) • Gravitational field measurements (interior structure) (1,2) • Ring occultations for particle size and ring thickness (4)	0	0	0	0	0	This instrument requires no Orbiter resources since it is part of the communications system.
Uplink radio science	• Neptune and Triton atmospheric pressure, temperature profiles, density (2)						This instrument requires no Orbiter resources since it is part of the communications system.
Bistatic radar	• Triton and possibly other satellite surface texture, mapping (3)	5	50		200		Possible to fly the source on the Orbiter and the receiver on the Triton lander.
Plasma wave instrument	• Plasma composition and electric fields (5)	5	5		5		
Magnetometer	• Magnetic fields (1,5)	25	3.1		4		The magnetometer is on a 15m boom. The 25kg mass indicated here is for a 5kg magnetometer and a 20kg boom. It is assumed that the magnetometer is a flux gate design.
Laser altimeter	• Triton topography (3)	12	25		100		The numbers used here were derived from Wayne Zimmerman's Lunar Precursor study with Team X although that spacecraft was assumed to fly at a 25km altitude, not 200km. The original values from the Neptune Orbiter with Probes Team X study were 10kg, 20W.
Microwave radiometer	• Neptune deep atmosphere composition (1,2) • Triton composition (3) • Neptune, Triton, icy satellite brightness temperatures (1, 2, 3, 6)	35	25		80		This instrument must be further studied for a refinement of the values indicated here. This is a passive instrument that is composed of a detector on an antenna. The aperture is not affected by the illumination. It is assumed that the gain is included in the 35kg value.

Table 3. Orbiter Instruments

Instrument	Measurements (Referenced to Science Goals and Objectives)	Mass CBE (kg)	Power Instrument (W)	Power Heaters (W)	Data Rate Compressed (bps)	Data Rate (bps)	Notes on Use / Heritage / Additional Comments
Bolometer Array	• Triton, icy satellite, and possibly ring surface temperature distribution (3, 4, 6)						This instrument was not discussed in the Team P study or in the original Team X session, but was included on the desired instrument list.
Ground Penetrating radar (GPR)	• Triton subsurface mapping, altimetry, surface emissivity / roughness (3) • Neptune deep atmosphere composition (1, 2) • Rings: particle size and thickness (4)	40	3000		1000	2500	The ground penetrating radar is 25-30% efficient. When the radar is on, it is conceivable that no other instruments will be operating. In comparing this instrument to other GPR instruments (on MRO and MARSIS), it turns out that at roughly 1- 25MHz, 40-60We, it is projected that penetration depths will be on the order, respectively, of 0.5-5Km with vertical resolutions in the 10-100m range. Each of the instruments is on the order of 20Kg. This data was provided by Sam Kim (JPL), a GPR developer.
Cosmic dust analyzer	• Cosmic dust measurements during transit from Earth to the Neptune system.	12.3	13.8		0.52	1.31	These mass and power values are based on a ratio of 75% of the CDA flown on Cassini. The assumed data rate is the same as the Cassini rate.
Totals		**171**	**3172.6**		**2921**	**5751**	

Table 4. Lander Instruments

Instruments	Measurements (Referenced to Science Goals and Objectives)	Mass CBE (kg)	Power Instrument (W)	Power Heaters (W)	Data Rate Compressed (bps)	Data Rate (bps)	Notes on Use / Heritage / Additional Comments
Surface Physical Properties Instrument (SPPI)	• Density (3) • Surface Porosity (3) • Surface thermal and electrical properties (3)	2.7	5	0	0.125	0.32	This instrument is essentially a weather station at Triton. It will make meteorology, measurements, including wind speed, etc. A boom is required to locate the SPPI package away from the lander. The mass listed in this table includes the boom and the spring mechanisms to deploy it. The indicated mass also includes two micro seismometers at 100g each, with one on the boom and one is redundancy. The data rate is based on the data rate of the ASI, but includes a 25bps addition for the seismometers.
Surface Science Package (SSP)	• Sampling device + analysis – GCMS (3) • Seismometer with active sounding (3) • Panoramic imager with color (3) • Surface NIR Spectrometer (3)	2.5	5	0	0.1	1	Assumed to be similar to Huygens instrumentation. The objectives of the surface science package can be met with a RAMAN-type instrument as the primary interest is geology.

Table 4. Lander Instruments

Instruments	Measurements (Referenced to Science Goals and Objectives)	Mass	Power		Data Rate		Notes on Use / Heritage / Additional Comments
		CBE (kg)	Instrument (W)	Heaters (W)	Compressed (bps)	Rate (bps)	
Panoramic Camera	• Required to return images from the surface (scientific and PR value).	3.5	27	2			Two cameras assumed for stereo imaging, redundancy, and range. The 3.5kg mass indicated here includes the 2 (0.25kg) cameras, a 1m high mast, and the actuators, cabling, etc.
Gas Chromatograph Mass Spectrometer (GCMS)	▪ Atmospheric Composition as a function of altitude (3) ▪ Measurement of Triton atmosphere during descent ▪ Profiles of N2, HCN, H_2S, NH_3 CH_4 H_20, etc.: Stratosphere to deep atmosphere (3) ▪ D/H (3) ▪ 15N/14N (3) ▪ Disequilibrium species (3) ▪ Hydrocarbons (3) ▪ Noble gases (He, Ne, Ar, Kr, Xe) (3) ▪ Isotopic ratios (3)	9	10	5	1	2.5	Stand-alone GC and MS experiments have been flown on Venus Probes. A mass spectrometer was flown on the Galileo Jupiter Probe. A GCMS flew on the Huygens probe as part of the Cassini-Huygens mission. Similar to instrument on Neptune probe except that Triton has a very thin atmosphere, so it may need to be compressed – the 1 kg difference between the lander and probe GCMS instruments is for the compressor. The GCMS is used both during descent and on the surface, assuming the other lander instrumentation can provide the atmospheric samples.
Atmospheric structure instrument (ASI)	• Atmospheric pressure/temperature as a function of altitude (3)	4	4	0	0.1	1	Similar to instrument on Neptune probe -- any difference is in the noise at this stage of the lander design.
Sampling mechanism	• Required to determine the composition of the Triton surface (3)	1.5	8	0	0.05	0.125	The ultra-sonic drill/corer (USDC) provides a low mass/low reaction force solution to obtaining shallow ice samples. The design planned for the Europa probe (JIML), uses a 1.5kg USDC housed in the instrument pod that can deliver a 1-1.5cc sample to a sample chamber which is then heated to release the volatiles for analysis by a GCMS. Power required is 25W. TRL is 4.
Totals		**23.2**	**59**	**7**	**1.38**	**4.94**	

(continued from **Technology Development Needs and Issues** section)

The Lander thermal design is equally challenging. Not only must internal temperatures be maintained above operating levels for the science instruments and Lander subsystems operating on the 35K Triton surface, the external surface of the Lander must not leak heat that could thermally contaminate the very surface under observation. In addition, the external instruments, including the sampling mechanism and other instrument sensors required to operate external to the Lander must be maintained above operating limits.

Two other lander technology development challenges include a deceleration system and a sophisticated autonomy design that will allow the Lander to perform the descent and surface mission, store the data, and transmit it to the overflying Orbiter once per month. Since Triton is without an appreciable atmosphere, an active propulsion system is required to slow the Lander down before it impacts the surface. This system must be capable of surviving a 13 year cruise to Neptune followed by the 4 year Probe/Orbiter missions and then, 17 years after launch, operate flawlessly to gently reach the Triton surface. The desire to limit the thermal pollution of Triton's surface dictates that the thrusters be turned off some meters before actually landing.

Nuclear Electric Power and Propulsion (NEP) Considerations

Use of nuclear electric power and propulsion enables the NOPL mission by providing generous power and mass capabilities while allowing tremendous flexibility in mission design. However, numerous engineering challenges remain. Another benefit of using the low thrust electric propulsion subsystem is the fact that the science instruments can operate continuously while the thrusters are firing.

Disadvantages in using NEP include the high levels of waste heat that must be radiated to space and the high radiation levels that the Orbiter, Probe and Lander electronics must withstand. In addition, use of NEP requires a vigorous PR campaign to educate the public on the safeguards in place during the launch and operation of the reactor.

Summary

A complex Neptune Orbiter with Probes mission, that includes Triton Landers, will benefit considerably from development of a nuclear electric power and propulsion capability for solar system exploration. Challenges abound in the development of the technologies necessary to support this ambitious mission. In addition, the extremely long mission duration, while daunting, must be viewed as a path to completing a comprehensive study of Neptune, Triton and the other Neptunian moons. The time required to traverse nearly the entire solar system in order to complete a comprehensive Neptune study should be considered as an investment in a mission that will undoubtedly be conducted only once in this century or perhaps in the centuries to come.

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